

Drell-Yan plus missing energy as a signal for extra dimensions

T. Han, D. Rainwater and D. Zeppenfeld

Department of Physics, University of Wisconsin, Madison, WI 53706

We explore the search sensitivity for signals of large extra dimensions at hadron colliders via the Drell-Yan process $pp \rightarrow \ell^+ \ell^- + \cancel{E}_T X$ ($\ell = e, \mu$) where the missing transverse energy is the result of escaping Kaluza-Klein gravitons. We find that one is able to place exclusion limits on the gravity scale up to 560 GeV at the Fermilab Tevatron, and to 4.0 (3.3) TeV at the CERN LHC, for $n = 3$ (4) extra dimensions.

I. INTRODUCTION

The idea of the existence of extra spatial dimensions has fascinated physicists for nearly a century [1]. A quantum theory of gravity seems to be consistent only via extension to extra dimensions [2]. If compactification of the extra dimensions occurs near the Grand Unification scale or the Planck scale $10^{16} - 10^{18}$ GeV, then the effects of quantum gravity would be accessible only at very high energy scales, beyond the reach of any collider experiment. In this case, one would have to understand the mechanism of weak scale stabilization (at about 100 GeV) against radiative corrections, the so-called hierarchy problem. Recently, a radical scenario has been advocated [3,4] wherein quantum gravity may become significant at a much lower energy scale (M_S), as low as $\mathcal{O}(\text{TeV})$. The apparent large Planck scale ($M_{pl} \sim 10^{19}$ GeV) is then attributed to the more rapid $1/r^{n+2}$ decrease of the gravitational force with distance in n extra space dimensions. In terms of the large compactification size, $R \gg 1/M_S$, of the extra dimensions this leads to¹

$$M_{pl}^2 \sim R^n M_S^{n+2}. \quad (1)$$

Such a scenario alleviates the hierarchy problem by restating it as a geometrical one, namely understanding the size of the compact dimensions and the scale M_S at which compactification occurs. This scenario could be realized in certain string formulations [7]. Naturally, after compactification, there will be towers of Kaluza-Klein (KK) excitations with mass separation of $\mathcal{O}(1/R)$. To avoid conflicts with the Standard Model (SM), it is assumed that the SM fields are stuck to a 4-dimensional hyper-surface, while only gravitons propagate in the extra dimensions. If we are interested in low-scale quantum gravity effects with $M_S \sim \mathcal{O}(\text{TeV})$, the minimal scenario $n = 1$ has been ruled out because $R \sim 10^8$ km, which would yield effects visible in planetary motion. For $n = 2$, although there is no conflict with Newtonian gravity or astronomy for $R \sim 0.1$ mm, the constraint from supernova cooling has put a bound on the scale up to $M_S > 50$ TeV [8]. One may even be able to push the scale up to $M_S > 110$ TeV from the spectrum for diffuse gamma radiation [9]. For $n > 2$, there is no experimental or observational conflict with the theory.

Most interestingly, there will be significant consequences for low-energy phenomenology with this scenario. Although the coupling for an individual KK excitation is gravitationally suppressed, the cumulative effect from the tower of states is suppressed only by $1/M_S^{n+2}$. Generically, there are two classes of collider signals induced by the KK gravitons. First, real KK gravitons can be emitted off SM fields. Second, virtual KK gravitons may be exchanged between external SM fields. There have been many studies proposing searches for visible signatures of extra dimensions at colliders [5,6,10–13]. In this Letter, we study another process to explore the sensitivity to probe low-scale quantum gravity effects, Drell-Yan charged lepton pair production, which has previously been used as a powerful test of the Standard Model and has provided severe constraints on new physics. For the process of current interest, we look for the clean signal

$$pp \rightarrow \ell^+ \ell^- + \cancel{E}_T X, \quad (2)$$

where the missing transverse energy \cancel{E}_T is due to an escaping KK graviton. We calculate the signal rate and those of the leading SM backgrounds, and study the sensitivity to probe quantum gravity effects both at the Tevatron and at the LHC.

¹The precise relation depends on the convention for R and M_S . It is taken to be $G_N^{-1} = 4\pi R^n M_S^{n+2}$ in [3]; and to be $G_N^{-1} = 8\pi R^n M_S^{n+2}$ in [5] where $G_N^{-1} = M_{pl}^2$ is the Newton's constant. For the convenience of calculations for physical quantities, we take the normalization to be [6] $G_N^{-1} = R^n M_S^{n+2} / (4\pi)^{n/2} \Gamma(n/2)$.

II. CALCULATIONAL TOOLS

The signal subprocess is

$$q\bar{q} \rightarrow \ell^+ \ell^- + G_{KK} \quad (3)$$

where $\ell = e, \mu$, and the graviton G_{KK} escapes the detector, resulting in missing energy. The signal can be described by fourteen tree level Feynman diagrams, seven each for Z and γ exchange, where a graviton is attached to each SM field and also to each SM vertex. Thus, off-shell effects of the Z boson are fully included. This would be extremely tedious to calculate by hand, or even with the aid of a trace-based Feynman graph program, but we can make this straightforward by using the helicity amplitude method: summing the numerical values of individual Feynman graph amplitudes for a set of fixed external helicities and momenta, then squaring the summed amplitude and integrating over all possible helicities and phase space numerically.

To do this, we constructed three new HELAS [14] vertex routines, for the graviton-fermion-fermion, graviton-gauge boson-gauge boson and graviton-fermion-fermion-gauge boson vertices [6]. Coding of the matrix elements can then easily be done by hand. We have verified current conservation for the full matrix elements both analytically and numerically. The summation over KK states with different mass is carried out numerically based on the weight function in [6].

As we are including photon interference effects, we must allow the Z to be off-shell, and thus must include finite-width effects for the Z propagators. This presents a problem for the calculation, as the graviton amplitudes are not gauge invariant for a Z propagator including an imaginary piece. While we believe we can provide a formal prescription for properly including such a term, for the moment we must rely on an approximation that is known to be extremely reliable [15]: we do not include a finite width in the matrix elements, but instead multiply the summed-squared amplitude by an overall factor

$$\frac{(\hat{s} - M_Z^2)^2}{(\hat{s} - M_Z^2)^2 + (M_Z \Gamma_Z)^2} \times \frac{(m_{\ell\ell}^2 - M_Z^2)^2}{(m_{\ell\ell}^2 - M_Z^2)^2 + (M_Z \Gamma_Z)^2} \quad (4)$$

where \hat{s} is the parton c.m. energy squared and $m_{\ell\ell}$ the invariant mass of the lepton pair. This factor removes the zero-width propagators from the matrix elements and inserts Breit-Wigner resonances for the Z boson. For phase space regions where the principal contribution comes from graphs where the incoming quark pair or outgoing lepton pair have invariant masses far from the Z mass, this factor is essentially unity. When either pair is at or near the Z mass, it approximates the full cross section by the correct resonant contributions.

III. RESULTS AND DISCUSSION

For the numerical evaluations, we use CTEQ4L parton distribution functions [16] and the EW parameters $m_Z = 91.19$ GeV, $m_t = 175.0$ GeV, $\sin^2 \theta_W = 0.2315$, and $G_F = 1.16639 \times 10^{-5}$ GeV⁻². We choose the factorization scale $\mu_f = E_T$ of the lepton system. We impose basic acceptance cuts for event identification, based on detector capability. These are

$$p_T(\ell) > 15 \text{ GeV}, \quad |\eta_\ell| < 2.0 \quad \text{for Tevatron}, \quad (5)$$

$$p_T(\ell) > 20 \text{ GeV}, \quad |\eta_\ell| < 2.5 \quad \text{for LHC}, \quad (6)$$

where $p_T(\ell)$ and η_ℓ are the transverse momentum and the pseudo-rapidity of a charged lepton.

A defining feature of the signal is the missing transverse momentum due to the escaping massive graviton. Also, most signal events are produced in association with a Z boson. The irreducible SM background to this signal is from $\ell^+ \ell^- \bar{\nu} \nu$ events, which are dominated by $Z^{(*)} Z$ and $\gamma^* Z$ production, which we call “Drell-Yan+ $\nu\nu$ ”. We want to reduce the photon continuum from $\gamma^* Z$ events where the virtual photon produces a relatively low mass lepton pair, and therefore require

$$E_T > 20 \text{ GeV}, \quad m_{\ell\ell} > 10 \text{ GeV}. \quad (7)$$

For the Tevatron at $\sqrt{s} = 1.8$ TeV (Run I) with these cuts, this SM background is 9.4 fb; at $\sqrt{s} = 2.0$ TeV (Run II) it rises to 11 fb. The slightly higher \sqrt{s} and greatly increased luminosity expected for Run II allow us to impose an additional cut on the missing transverse energy,

$$E_T > 100 \text{ GeV}, \quad (8)$$

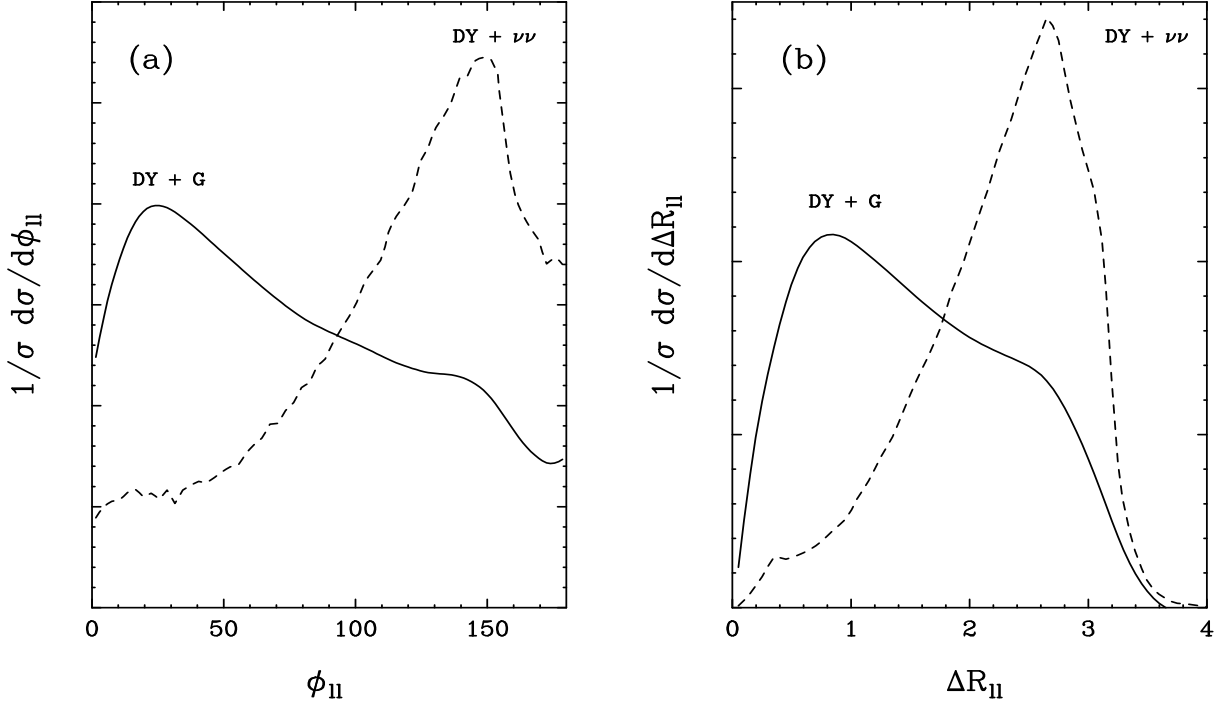


FIG. 1. Normalized distributions of the lepton pair at the LHC: (a) azimuthal opening angle $\phi_{\ell\ell}$; (b) $\Delta R_{\ell\ell}$. The $n = 3$ graviton signal is shown with the solid curves, and the SM background with the dashed curves.

reducing the SM background to only 1.25 fb.

The much higher \sqrt{s} available at the LHC allows for the emission of much heavier gravitons and for a significant recoil of the dilepton system. This is reflected in the normalized dilepton angular distribution of Figure 1, for an $n = 3$ signal and the $DY + \nu\nu$ background: (a) azimuthal opening angle $\phi_{\ell\ell}$; and (b) separation $\Delta R_{\ell\ell} = \sqrt{\phi_{\ell\ell}^2 + (\eta_{\ell_1} - \eta_{\ell_2})^2}$. These plots show distinct differences for the signal and background. The final state leptons of the signal are preferentially emitted in the same direction, close to each other, while in the background the leptons tend to be more back-to-back. We can thus impose further cuts on the leptons, requiring

$$\phi_{\ell\ell} < 90^\circ, \quad \Delta R_{\ell\ell} < 1.2. \quad (9)$$

This heavy graviton emission will also result in the signal exhibiting a much harder E_T spectrum, as shown in Fig. 2. We therefore suggest an even higher E_T cut for the LHC,

$$E_T > 150 \text{ GeV}. \quad (10)$$

After the cuts of Eqs. (6,7,9,10), the SM background at the LHC is 2.8 fb.

A feature of any effective theory is that it is a low-energy approximation and can not be trusted at large energies, comparable to the defining scale of the theory. Applying this rule to the present case, our calculation requires some additional care for $n > 2$, as a non-trivial fraction of those signal events occur at center of mass energies $\sqrt{s} > M_S$. A conservative estimate of the signal is obtained by discarding any events with $\sqrt{s} > M_S$ [5]. More generally one could invoke form-factor damping of the high energy region. To obtain estimates of the string scales which can be probed experimentally we employ an iterative procedure, starting with a seed value for M_S and throwing away all events with $\sqrt{s} > M_S$. The resulting signal cross section is used to recompute a new exclusion limit for M_S , assuming a simple scaling behavior of the signal cross section, $\sigma_{\text{signal}} \sim 1/M_S^{n+2}$. Using the new exclusion limit as the upper bound on the allowable \sqrt{s} range, one obtains a stable exclusion limit in only 2-3 iterations. However, for $n > 4$ most of the signal events populate this unphysical region, and the overlap of the validity range of the effective theory with the range which would provide for a visible signal shrinks to zero. In this situation, one is unable to obtain any reliable estimate for a probe to M_S via E_T signals. Instead, one would expect to first observe string excitations of particles states as a signature for new physics [13].

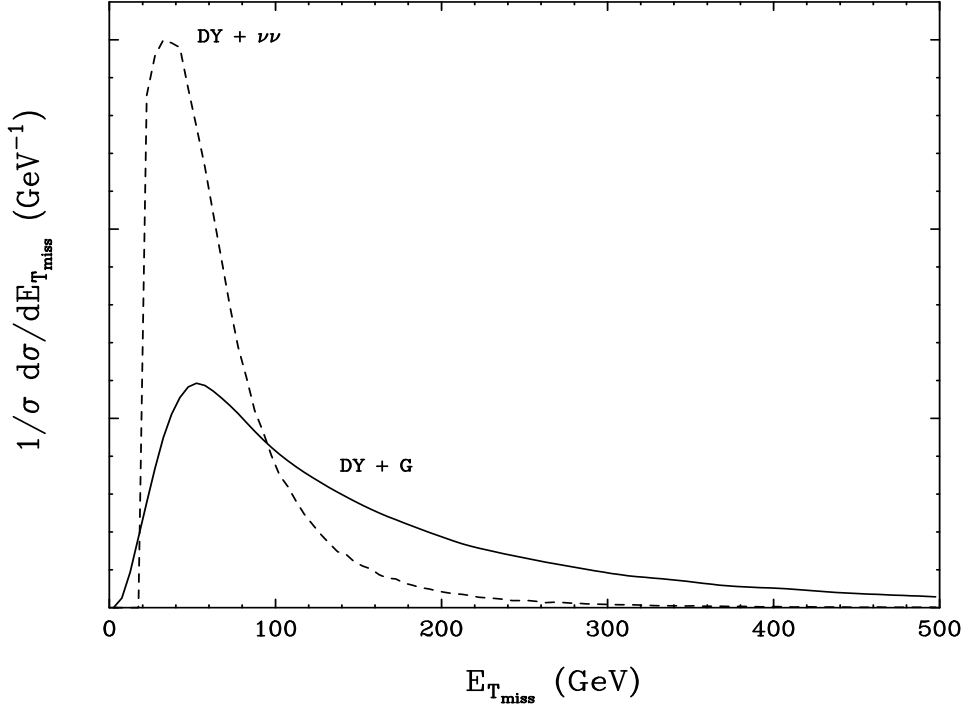


FIG. 2. Normalized missing transverse momentum distributions of the $n = 3$ graviton signal (solid) and SM background (dashed) for the LHC.

	$n = 2$	$n = 3$	$n = 4$
Tevatron Run I @ 0.2 fb^{-1}	0.9		
Tevatron Run II @ 10 fb^{-1}	1.5	0.56	
LHC @ 100 fb^{-1}	5.3	4.0	3.3

TABLE I. String scale M_S 95% CL exclusion limits (TeV) at the Tevatron and LHC for $n = 2, 3, 4$ extra dimensions. For the Tevatron Run I value, we have imposed the cuts of Eqs. (5,7), and the additional cut of Eq. (8) for the Tevatron Run II, while for the LHC the cuts are given by Eqs. (6,9,10). The limits take into account the $\sqrt{\hat{s}} < M_S$ requirement discussed in the text.

In Table I, we summarize the sensitivity reach to the scale M_S for $n = 2 - 4$ via the process of Eq. (2) at the Tevatron and the LHC. We see that this mode is a quite promising search channel. Although the Tevatron can impose some bounds, it is much more impressive to search for the signal at the LHC, its reach being several TeV for $n = 3, 4$ extra dimensions.

A comparison with other studies at hadron colliders is in order. While the monojet+ \cancel{E}_T signal [5,10] from processes like $q\bar{q} \rightarrow g G_{KK}$ has the largest rate, it also has much more severe QCD backgrounds, mostly due to the mismeasurement of jets in the forward regions of the detector. Ref. [10] obtained results comparable to ours. For instance, at the LHC a 95% CL limit is expected for $M_S = 6.4$ (3.5) TeV with $n = 2$ (4). On the other hand, Ref. [5] reached a more impressive conclusion, claiming a 5σ discovery for $M_S = 14$ (6.0) TeV with $n = 2$ (4) extra dimensions². Alternatively, the virtual G_{KK} contribution to the DY process of $q\bar{q} \rightarrow \ell^+\ell^-$ can be also significant. It was found that a 95% CL limit can be reached a scale $\Lambda \sim 1$ (6) TeV at the Tevatron and the LHC [11], with a little dependence on n . However, one would have to introduce an additional assumption for a cutoff scale Λ_{above} which the virtual KK tower is truncated, making a direct comparison of M_S exclusion limits from external G_{KK} production versus virtual exchange difficult.

²We have converted the scale M_S to our normalization convention.

IV. CONCLUSIONS

We have explored the search sensitivity for signals of large extra dimensions at hadron colliders via the Drell-Yan process $pp \rightarrow \ell^+ \ell^- + \cancel{E}_T X$ ($\ell = e, \mu$) where the missing transverse energy is the result of escaping Kaluza-Klein gravitons. This is a very clean channel for hadron collider physics. We find that one is able to place exclusion limits on the gravity scale up to 560 GeV at the Fermilab Tevatron, and up to 4.0 (3.3) TeV at the CERN LHC, for $n = 3$ (4) extra dimensions. This reach is comparable to one found in previous studies of the monojet+ \cancel{E}_T process [10] and for virtual contributions of G_{KK} to the DY process [11].

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